High Speed Devices Based on Lattice Matched and Pseudomorphically Strained Quantum Wells for Optoelectronic Integrated Circuits

Progress Report

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1. INTRODUCTION

The main objectives of this project is to develop InP–based lattice–matched and pseudomorphic quantum well materials using the MBE and MOMBE techniques, study their optical and electro–optic properties, and realize very high–speed external modulators with them. At the final stages we hope to realize OEICs with the lasers and modulators on the same chip. With these objectives, we have initiated work in the following areas, with both theory and experiments and the results are briefly described.

2. GROWTH AND OPTICAL CHARACTERIZATION OF InGaAs/InAlAs MQW

We have grown a series of MQW under well–controlled MBE conditions, to be described in the next section. We have made variable temperature photoluminescence and absorption measurements. The linewidth of the excitonic peak in the low–temperature PL is 5.7 meV, which, to our knowledge is the lowest achieved in this MQW system. We have analyzed temperature–dependent linewidth data to obtain the homogenous and inhomogenous components of the linewidth and carrier lifetimes. Low–temperature absorption spectrum (Fig. 1) clearly shows band–to–band, and excitonic transitions upto $n = 3$, which also confirms the high quality of the samples. Finally, we have measured, for the first time, the lifetime of carriers in the $n = 1$ and $n = 2$ bound states MQW by picosecond time–resolved photoluminescence using the correlation spectroscopy technique. We find that the carrier lifetime limited by non–radiative processes is 600–800 ps, as shown in Fig. 2.

3. ELECTRO–OPTIC EFFECT IN PSEUDOMORPHIC InGaAs/InAlAs/InP MQW

Biaxial strain in quantum wells changes the energy separation and coupling between the heavy hole (HH) and light hole (LH) excitonic transitions. In the case of compressive strain, the HH absorption dominates the absorption edge, while in the case of tensile strain the light 9hole absorption dominates. Since the TE mode couples to the HH while the TM mode couples to the LH, this HH – LH splitting is expected to play an important role in determining the electro–optic properties. The effect of biaxial strain on the electro–optic effect in quantum wells have not been investigated in detail, both theoretically and experimentally, other than some preliminary experiments by us on InGaAs/GaAs MQW. We have focused on the use of strain to influence the excitonic resonances. Experimental results show the effect of compressive and tensile strain on the refractive index changes. Measurements are carried out on molecular beam epitaxial (MBE) $In_xGa_{1-x}As/Al_{0.2}Ga_{0.8}As$ MQW structures for compressive strain and metallorganic chemical vapor deposition (MOCVD) $In_{0.53\pm x}Ga_{0.47\mp x}As$/InGaAsP structures for compressive and tensile strain. The phase shift is measured as a function of applied bias in waveguide electro–optic devices. Far from the excitonic resonances the Δn vs. E–field relation is linear, but it develops a quadratic behavior as one approaches the exciton peak. The measured phase shifts as a function of strain in InGaAs/InGaAsP MQW are shown in Fig. 3. Theoretical results including the important HH–LH band mixing effect are presented for the electro–optic effect. We calculate the absorption coefficient directly from the computed bandstructure and compute the associated refractive index change by using the Kramers–Kronig transform. In particular, the contribution of the excitonic part is discussed. The data is the first ever reported (i) detailing the effects of strain on the electro–optic coeffients and (ii) calculating the effect of strain on the electro–optic coefficients with the inclusion of excitons.

4. TUNNELING AND RECOMBINATION TIMES IN QUANTUM WELLS

The ultimate speeds of Stark–effect modulators will be limited by field–dependent tunneling rates of electrons and holes in quantum wells. We are measuring the tunneling rates of electrons and holes in specially designed structures for both GaAs- and InP–based quantum wells with a Hamamatsu streak camera. In the case of GaAs/AlGaAs QW, we are also investigating the effects of indirect (bandgap) barriers. Field dependent tunneling of electrons and holes was studied by first creating e–h pairs in the GaAs well by a picosecond laser and then studying the luminescence by a streak camera with a resolution of 10 ps. A rapid decrease in the electron tunneling rate is observed when the barrier becomes indirect. For example, with no transverse bias, the tunneling time increases by more than 100 ps as one goes grom a direct to indirect barrier of AlGaAs 50Å thick.

Theoretical results are based on studying the time evolution of an electron (hole) wave packet under the influence of a (4 x 4) $\mathbf{k} \cdot \mathbf{p}$ Hamiltonian which includes band mixing effects. Strong suppression of the escape rate is found (in absence of any scattering process) when the well and barrier symmetries are different. Comparison with experimental results are good.

5. BROADBAND MATCHING NETWORK FOR HIGH–FREQUENCY MODULATORS

At the present time the highest bands of electro–optic and Stark effect modulators are 6 and 20 GHz respectively. We will explore the extrinsic limitations and investigate techniques to increase this bandwidth. However, an important problem is the design of a broadband matching network with which the microwave modulating signal can be effectively coupled. We have begun work on the design of both lumped and distributed networks.

PAPERS AND CONFERENCE PRESENTATIONS

1. "Electro–Optic Effect in Strained and Lattice–Matched MQW Structures – Role of Excitonic Resonances," J. Pamulapati, J. P. Loehr, J. Singh, P. K. Bhattacharya, and M. J. Ludowise, to be presented at the *5th International Conference on the Physics of Electro-Optic Microstructures and Microdevices*, Crete, July 1990.

2. "Optical Properties of High Quality MBE Epitaxial InGaAs/InAlAs Multiquantum Wells," S. Gupta, J. Pamulapati, and P. K. Bhattacharya, *Journal of Applied*

Physics, under preparation.

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Low temperature (14 K) absorption spectra of InAlAs / InGaAs MQW sample

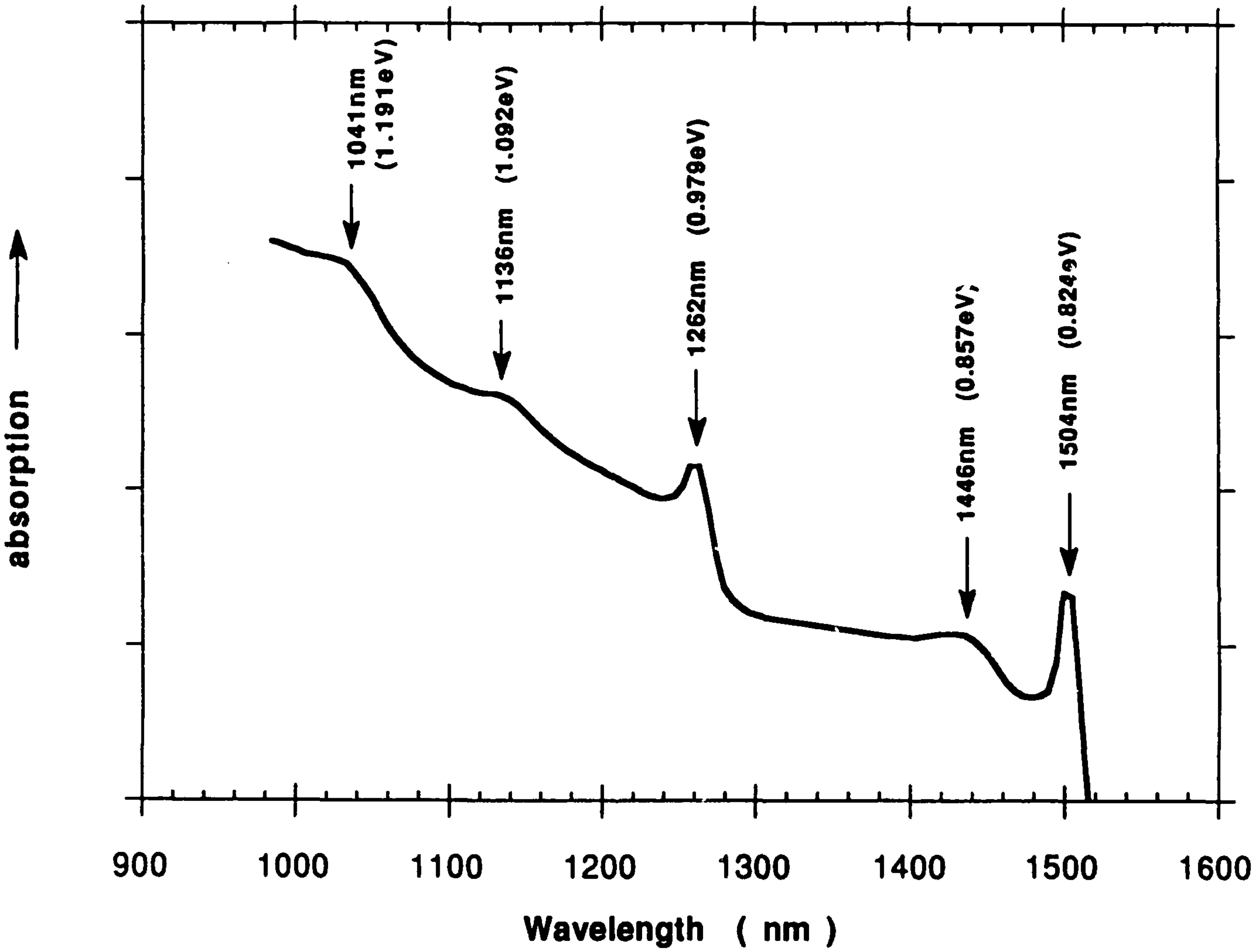

Figure 1

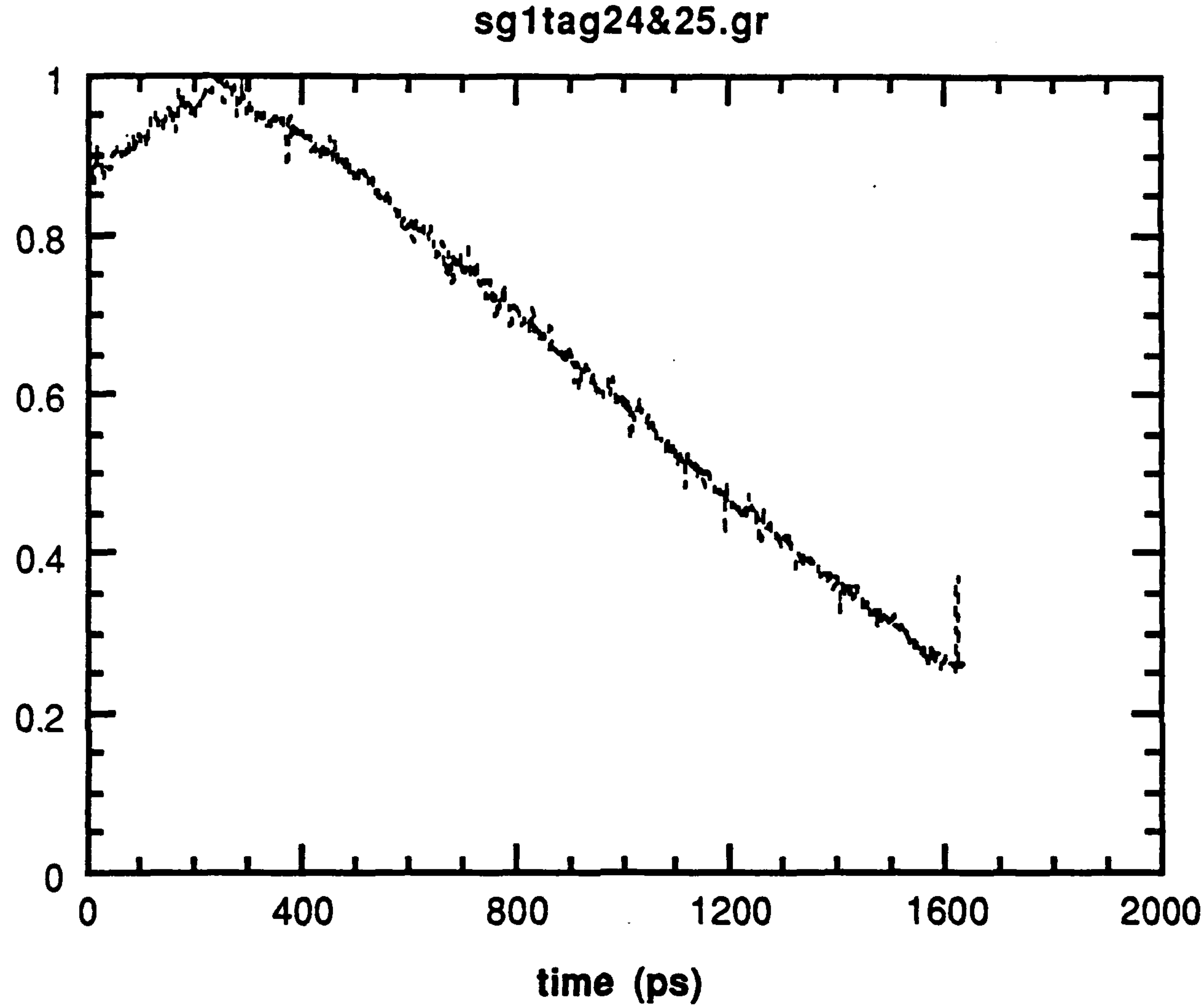

Figure 2 Time–resolved PL corellation data for InGaAs/InAlAs MQW at zero bias. A carrier lifetime of 800 ps is obtained from analysis of this data.

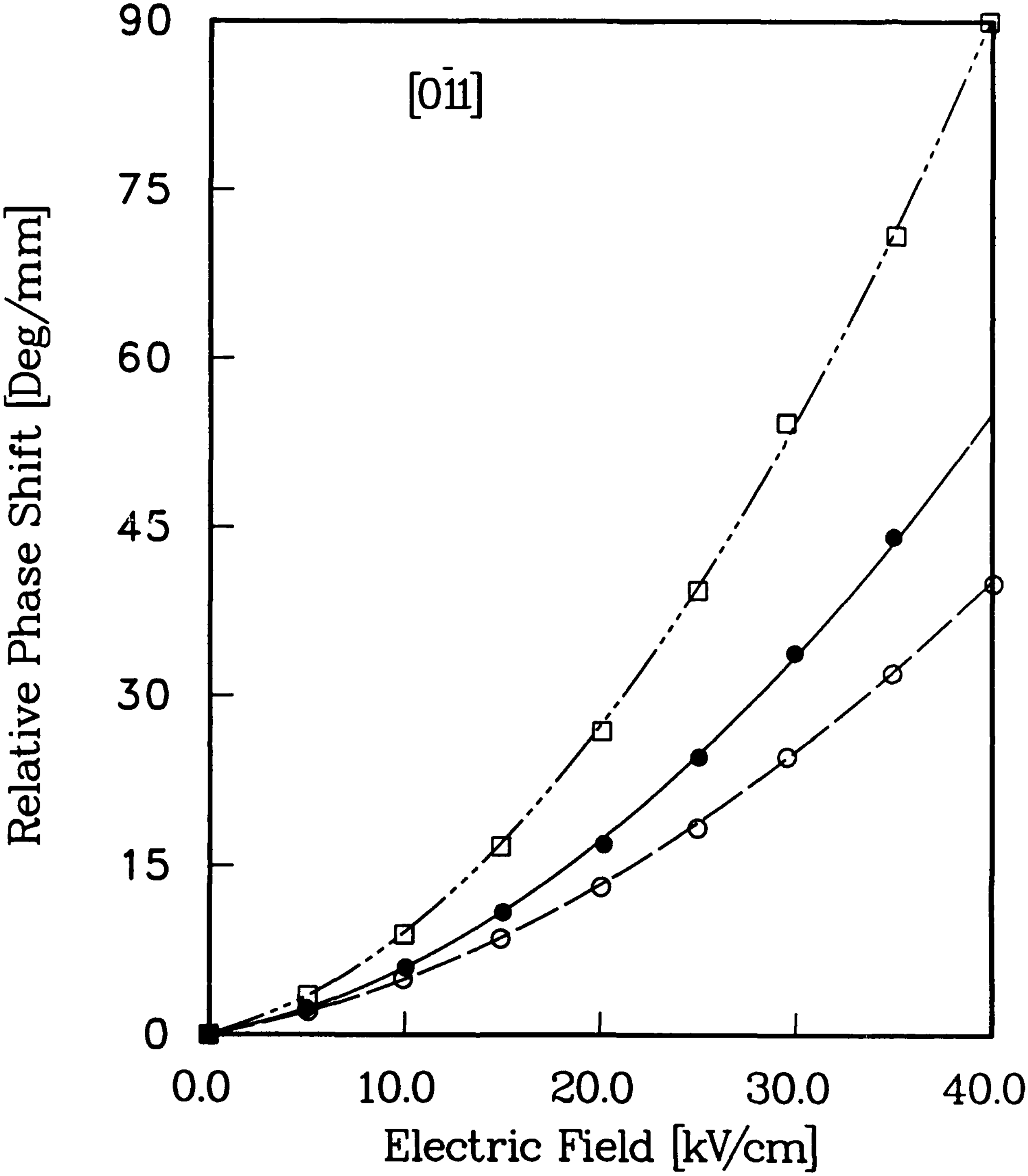

Figure 3 Measured electro–optic phase shift in InGaAs/InGaAsP quantum wells.